Maintenance Practices for Emergency Diesel Generator Engines Onboard United States Navy Los Angeles Class Nuclear Submarines

by

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Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degrees of

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and
Master of Science in Mechanical Engineering
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ABSTRACT

The United States Navy has recognized the rising age of its nuclear reactors. With this increasing age comes increasing importance of backup generators. In addition to the need for decay heat removal common to all (naval and commercial) nuclear reactors, naval vessels with nuclear reactors also require a backup means of propulsion. All underway Navy nuclear reactors are operated with diesel generators as a backup power system, able to provide emergency electric power for reactor decay heat removal as well as enough electric power to supply an emergency propulsion mechanism. While all commercial nuclear reactors are required to incorporate multiple backup generators, naval submarine nuclear plants feature a single backup generator. The increasing age of naval nuclear reactors, coupled with the dual requirements of a submarine's solitary backup generator, makes the study of submarine backup generators vital.

This thesis examines more than 7,000 maintenance records dated 1989 to 2005 for emergency diesel generator engines onboard Los Angeles class nuclear submarines. This class of submarines, which features the Fairbanks Morse 8-cylinder air-started opposed-piston diesel engine, is expected to continue to operate until at least 2020. An analysis of corrective and routine maintenance tasks was conducted. Analysis included the diesel engine as well as its subsystems of diesel lube oil, diesel freshwater, diesel seawater, diesel air start, and diesel fuel oil. The analysis centered on maintenance task times and costs. Time factors analyzed included the time between maintenance actions, the time awaiting parts, the time to conduct the maintenance, and the impacts on operational availability. Cost factors analyzed included the material costs and the manpower costs (both sailors and off-hull workers). As patterns were recognized, high impact items were highlighted and recommendations to reduce risk to operational availability were given.

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List of Acronyms

AD	Destroyer Tender
A_O	Operational Availability
AS	Submarine Tender
CASREP	Casualty Report
CSMP	Current Ship's Maintenance Plan
EIC	Equipment Identification Code
FY	Fiscal Year
IMA	Intermediate Maintenance Activity
JCN	Job Control Number
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NAVSEA	Naval Sea Systems Command
NNPI	Naval Nuclear Propulsion Information
PMS	Preventative Maintenance System
SSN	Submersible Ship, Nuclear
SUBMEPP	Submarine Maintenance, Engineering, Planning, and Procurement Activity

Chapter 1 Introduction

United States Navy operational submarines are nuclear powered. Future submarines will continue to be nuclear powered, unless non-nuclear propulsion processes can make improvements in their mobility and endurance.

> "Diesel submarines are the wrong ships for the United States. Diesel (and other non-nuclear propelled) submarines do not match the forward, globally oriented responsibilities and strategy of the United States and cannot operate far from U.S. shores for extended periods. They do not have the mobility, covertness, endurance, or firepower to meet U.S. military requirements for submarines…. Because of their stealth, endurance, and multi-mission capability, and lethality, nuclear submarines conduct missions that no one else can replicate, and offer American taxpayers a tremendous return on investment. SSNs pack enormous capability into a very small space. Nuclear-powered submarines are in a class by themselves. No other weapon platform provides the survivability, maneuverability, and sustainability - combined with firepower - of an SSN." [1]

This reliance on nuclear power necessarily implies a reliance on a means to remove reactor decay heat in the event of a reactor shutdown. Both military and civilian nuclear reactors need emergency diesel generators to power decay heat removal equipment in the event of a loss of electrical power. "Every [commercial] nuclear power plant has at least two diesel generators that provide emergency electrical power in the event that all offsite electrical power is lost." [2]

Submarine emergency diesel generators are especially critical for several reasons.

- They power equipment to remove decay heat from the reactor.
- They power equipment that provides emergency propulsion for the submarine at sea.
- They provide one of the two means of ventilating the submarine.
- Weight and volume considerations restrict the number of emergency diesel generators to one per submarine.
- Limited weight and volume (and therefore capacity) is allotted to the submarine main storage battery.
- The average age of US submarine nuclear reactors will increase.

Although his emphasis was on designing and building rugged, reliable and safe reactor plants, US Navy Admiral K. H. Donald's comments affirm the submarine's increased dependence on the emergency diesel generator. ADM Donald is the Director of Naval Nuclear Propulsion.

> “The key challenge in fleet support is the fact that our plants are aging. The average reactor plant has operated for about 19 years in 2004 and that will increase to nearly 24 years in 2011. With this aging come complexities and some occasional surprises.”[3]

These older reactor plants will for the most part be onboard Los Angeles class submarines, as reported by the Director of Submarine Warfare, Rear Admiral Joseph Walsh. “Looking out to 2011, four out of five submarines in the Submarine Force will be 688 Class submarines.”[4] Serious consideration needs to be given to the systems responsible for responding in the event of a submarine nuclear reactor incident. One of those systems is the emergency diesel generator. This thesis analyzes maintenance records for the emergency diesel generator carried on the Los Angeles class submarines.

The specific diesel carried onboard all Los Angeles class submarines is the Fairbanks Morse opposed piston 8 cylinder 850kW 720rpm 1207hP engine-generator. The support systems include diesel lube oil, diesel freshwater, diesel seawater, diesel air start, and diesel fuel oil. Maintenance records pertaining to the diesel engine and its support systems were analyzed.

Chapter 2 Conduct and Recording of Diesel Engine Maintenance

2.1 Types of Maintenance

Navy maintenance conducted generally falls in to two categories – preventative and corrective. These maintenance actions may or may not require replacement parts, and may or may not require significant man-hour expenditures. Regardless of the effort required, every preventative and corrective maintenance action is recorded in the Current Ship's Maintenance Plan (CSMP).

Although some experimentation has been made in the area of condition-based maintenance, the fleet continues to rely on the Preventive Maintenance System (PMS). [5] The preventative maintenance is performed primarily by sailors assigned to the submarine (Ship's Force), but some maintenance items require the assistance of the local Intermediate Maintenance Activity (IMA).

Corrective maintenance is also primarily performed by Ship's Force, but may also require assistance from the local IMA. Failures of high import are generally considered equipment "casualties" and are additionally reported from the individual submarine to higher authority by submitting a Casualty Report (CASREP).

As stated earlier, the diesel generator supplies power to decay heat removal pumps in the event of an extended reactor shutdown at sea. Thus, the consequences of a diesel generator failure are serious. In addition to regularly scheduled maintenance, qualified inspectors periodically perform diesel engine inspections. [6]

2.2 Maintenance Record Availability

Not all submarine diesel engine maintenance records are available for public consumption.

Information about submarine diesel engines is indirectly related to the nuclear propulsion plant. Information related to the propulsion plant can be designated as Naval Nuclear Propulsion Information (NNPI). Generally, NNPI is not made publicly available. NNPI was not used in the completion of this thesis.

Information relating to the location or operating patterns of submarines is also generally

classified and not available to the public. In addition to information regarding the nature of the failure or malfunction of the equipment involved, CASREPs generally also include information about the location of the submarine experiencing the casualty. For this reason, CASREP reports are classified and were not available for use in this thesis.

Submarine diesel engine inspection records were also deemed to be not publicly releasable, for reasons neither readily apparent nor adequately explained to the author.

The CSMP, which contains both preventative and corrective maintenance actions, is generally not classified. These records were made available.

Chapter 3 Preliminary Review of Diesel Engine Maintenance Records

3.1 Raw Data

Maintenance records for all 62 Los Angeles class submarines dating from 1989 to 2005 were obtained from the Submarine Maintenance, Engineering, Planning, and Procurement (SUBMEPP) Activity. A list of maintenance record fields with their meanings is shown in [Table 1] below. The meanings are taken from reference [7].

Table 1: Maintenance Record Fields

Maintenance Record Fields	Meaning
Action Taken Code	Describes the action taken to complete the maintenance, using a single digit and, if necessary, a single letter.
Cause Code	Describes the primary or overriding cause of the failure or malfunction when the need for maintenance was first discovered.
CSMP Narrative Summary	Current Ship's Maintenance Plan condensed (30 characters or less) description of the problem.
Date Closing	The date the work request was signed off as complete.
EIC	Equipment Identification Code, a seven-character code that identifies the equipment
Equipment Nomenclature	Noun name of the equipment (should match the Equipment Identification Code).
JCN	Job Control Number – a unique identifier consisting of the submarine Unit Identification Code, the Work Center, and the Job Sequence Number.

Table 1: Maintenance Record Fields (continued)

Maintenance Record Fields	Meaning
Narrative Data	Describes what is wrong and what needs to be done.
Priority Code	Priority of the maintenance item (mandatory, essential, highly desirably, desirable).
Safety Code	If necessary, used to indicate the level of safety issue resulting from the failure or malfunction.
Ship Class	Restricted to Los Angeles Class (SSN 688)
Ship Type Hull	Individual hull numbers (SSN 693, SSN 760, etc.)
Status Code	Describes the effect of the failure or malfunction on the operational capability of the equipment when the need for maintenance was first discovered.
Total IMA Man Hours	Hours expended by the Intermediate Maintenance Activity (not the submarine's crew).
Total Repair Replacement Cost	Expenditure on repair parts only.
Total Ship Force Man Hours	Hours expended by the submarine's crew after submitting initial maintenance request.
When Discovered Code	Identifies when the need for maintenance was discovered (during operation, startup, shutdown, inspection, etc.)
When Discovered Date	Date the failure or malfunction was discovered.

Not all 62 submarines were in commission during the years covered by the maintenance records (1989-2005). A list of commissioning and decommissioning dates is provided in [Table 2] below. [8, 9]

Table 2: Los Angeles Class Submarine Commissioning and Decommissioning Dates

Hull Number	Comm. Date	Decomm. Date	Hull Number	Comm. Date	Hull Number	Comm. Date
688	11/13/76		713	9/25/82	762	7/24/93
689	6/25/77	11/1/93	714	5/21/83	763	1/8/94
690	6/25/77		715	11/5/83	764	11/7/92
691	12/17/77		716	5/12/84	765	3/13/93
692	3/11/78	2/7/95	717	11/17/84	766	9/16/94
693	6/10/78	1/5/95	718	7/6/85	767	11/6/93
694	7/8/78	9/16/96	719	7/27/85	768	12/10/94
695	12/16/78	3/27/97	720	11/23/85	769	2/24/95
696	3/3/78	12/1/95	721	9/27/86	770	8/18/95
697	1/5/80	4/1/98	722	9/12/87	771	10/9/95
698	3/28/81		723	7/9/88	772	2/16/96
699	5/16/81		724	11/8/86	773	9/13/96
700	7/18/81		725	7/11/87		
701	10/24/81		750	6/3/89		
702	12/19/81	9/18/97	751	8/6/88		
703	1/30/82	3/1/99	752	2/11/89		
704	7/24/85	10/1/97	753	4/7/90		
705	1/8/83		754	10/21/89		
706	5/21/83		755	6/30/90		
707	10/1/83	9/10/04	756	1/26/91		
708	3/17/84		757	6/29/91		
709	9/8/84		758	9/28/91		
710	9/19/85		759	2/29/92		
711	4/24/81		760	4/11/92		
712	3/6/82	3/1/99	761	1/9/93		

3.2 Ensuring Unique, Relevant Records

A total of 7019 records were examined. An analysis of the Job Control Number revealed 2401 records were duplicates of other records in all fields except Narrative Data. These Narrative Data comments were appended to the original matching record.

Of the remaining 4618 records, three records were misclassified; these records did not involve the diesel engine or its support systems. Sixty records belonged to AD 41 or AS 39 ship classes. Seven belonged to a diesel engine at Naval Submarine School. Fifteen records had invalid JCNs and could not be attributed to Los Angeles class submarine emergency diesel engines.

Of the 4533 remaining records, eleven records had unique JCNs but were upon closer inspection determined to be redundant records. The redundant records had (1) identical When Discovered Dates and Dates Closing, (2) an Action Taken Code of 4 (Canceled), (3) a Total Ship Force Man Hours of 1, and (4) a record with the next sequential Job Control Number that described the identical issue. 4522 unique, relevant records remained for further analysis.

3.3 Additional Data Fields and Key Metrics

Several additional maintenance record fields were necessary for analytical use. These additional fields are described in [Table 3] below.

Table 3: Additional Maintenance Fields

Maintenance Record Fields	Meaning
Elapsed Days	The difference between Date Closing and When Discovered Date. This differs from the traditional Time To Repair in that the When Discovered Date and Date Closing do not necessarily coincide with the commencement and conclusion of repair, respectively.
Total Hours	The addition of Total IMA Man Hours and Total Ship Force Man Hours.
Fiscal Year	The fiscal year based on the Date Closing.

Table 3: Additional Maintenance Fields (continued)

Maintenance Record Fields	Meaning
Inflation Index	Using 2006 as the base fiscal year (1.0), an index is calculated based on 4.0% inflation using the simple formula: Inflation Index = $1.04^{(2006 - FY)}$
FY06 Repair Cost	Adjusts the Total Repair Replacement Cost to the current fiscal year by the multiplying it by the Inflation Index.
FY06 IMA Labor Cost	Uses current labor rates of $60/hour applied to Total IMA Man Hours.
FY06 S/F Labor Cost	Uses current labor rates of $30/hour applied to Total Ship Force Man Hours. This is based on the generic enlisted sailor personnel cost of $60,000 annually (salary and benefits).
FY06 Labor Cost	IMA Labor Cost plus S/F Labor Cost.
FY06 Total Cost	Adds the Repair Cost and the Labor Cost.
Hourly Labor Rate	Divides the FY06 Labor Cost by the Total Hours.
Time Since Last Maintenance Action	The difference between the Date Closing of the most recent previous maintenance action on the same Ship Type Hull and the When Discovered Date of the current maintenance action. This differs from the traditional Time Between Failures in that more than one maintenance action can be ongoing at any one time.

From these additional data fields, five key metrics were chosen: Elapsed Days, Total Hours, FY06 Repair Cost, FY06 Labor Cost, and FY06 Total Cost. These metrics are further analyzed in Chapter 4.

3.4 Records Affecting Operational Availability

Operational availability (A_O) is simply the ability for the submarine to effectively perform its mission. A submarine would ideally have an operational availability of one, but a more typical operational availability would be on the order of 0.6. This figure would mean that

the submarine is ready to perform its mission 60 percent of the time, on average. Planned or unplanned periods of heavy maintenance impact operational availability.

Whether diesel engine maintenance actions impacted operational availability or not can be gleaned from analyzing the maintenance record fields Priority Code, Safety Code, and Status Code. A Priority Code of 1 (mandatory) or 2 (essential), or a Safety Code of 1 (critical safety or health deficiency) or 2 (serious safety or health deficiency), or a Status Code of 2 (non-operational) would indicate an action adversely affecting operational availability. The total number of maintenance actions meeting at least one of these criteria was 1277, or 28 percent of the 4522 unique, relevant records.

Additional analysis was performed on these records. In an effort to determine availability for the diesel engine onboard each submarine, or Ship Hull Type, two quantities were established. The average Time Since Last Maintenance was considered analogous to the Mean Time Between Failures (MTBF), and the average Elapsed Days was considered analogous to the Mean Time To Repair (MTTR). An availability measure (A) was established to be the following:

$$A_{ShipHullType} = \frac{MTBF_{ShipHullType}}{MTBF_{ShipHullType} + MTTR_{ShipHullType}}$$

An availability measure of 1.0 would indicate that, no matter how often the diesel engine failed, the repair took no time to effect, so the machine was always available. An availability measure of 0.0 would indicate that, no matter how fast the repair could be completed, the machine would fail as soon as the repair was complete and thus never be available.

Chapter 4 Analysis Results

The key metrics for the maintenance records are shown in [Table 4] below, compared with averages for all records and for those records not affecting operational availability. The key metrics are individually discussed below.

Table 4: Key Metric Averages

	Elapsed Days	Total Hours	FY06 Repair Cost	FY06 Labor Cost	FY06 Total Cost
All Records	89 days	43 hours	$654	$1597	$2251
Records Affecting A_O	94 days	72 hours	$1042	$2924	$3966
Records Not Affecting A_O	87 days	31 hours	$502	$1075	$1577

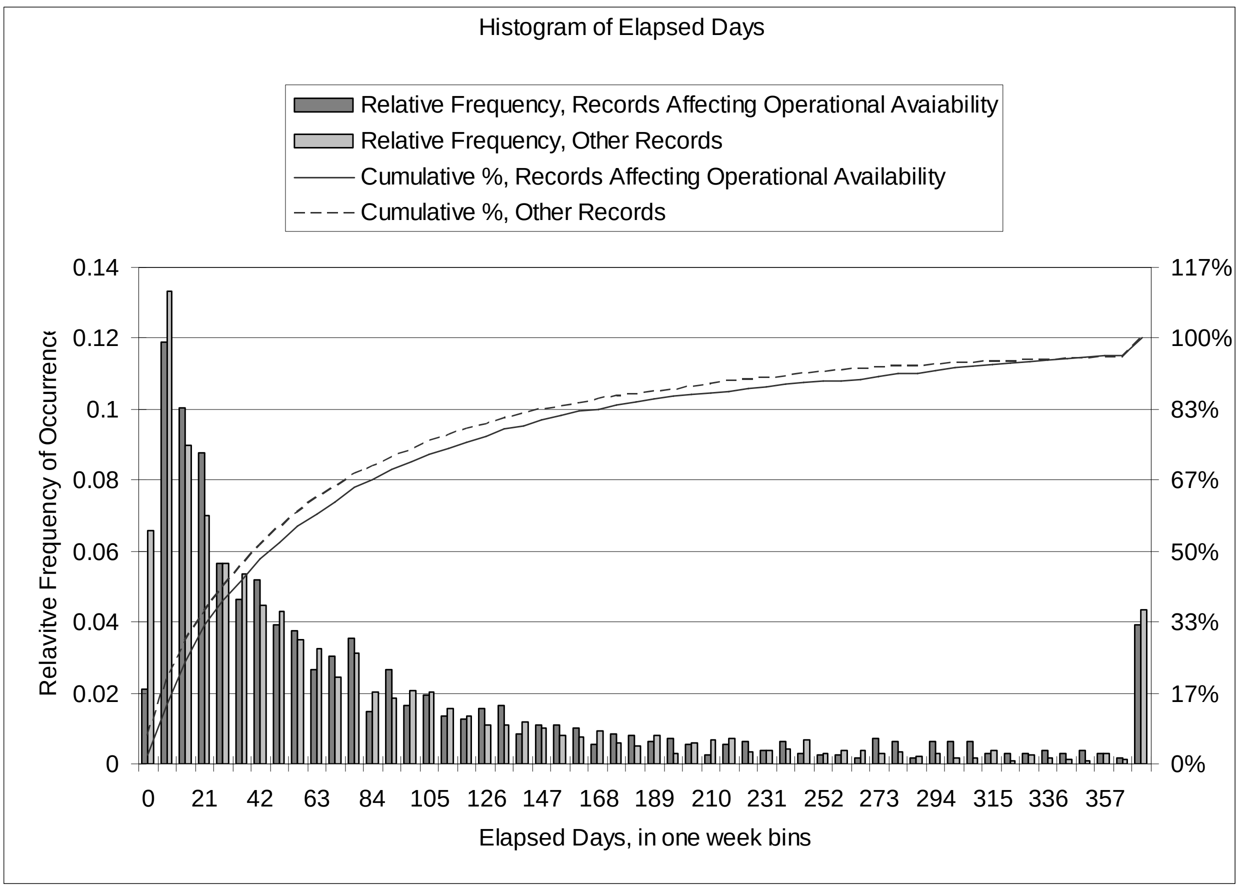
4.1 Elapsed Days

The similar elapsed days, shown in [Table 5] and [Figure 1] below, calls into question the definitions for Priority Code, Status Code, and Safety Code. If the records affecting A_O truly were a higher priority, why were they not completed faster than other records?

Table 5: Comparison of Elapsed Days

Elapsed Days	Average	70 percent at or below	90 percent at or below
All Records	89 days	88 days	231 days
Records Affecting A_O	94 days	94 days	255 days
Records Not Affecting A_O	87 days	84 days	221 days

Figure 1: Histogram of Elapsed Days



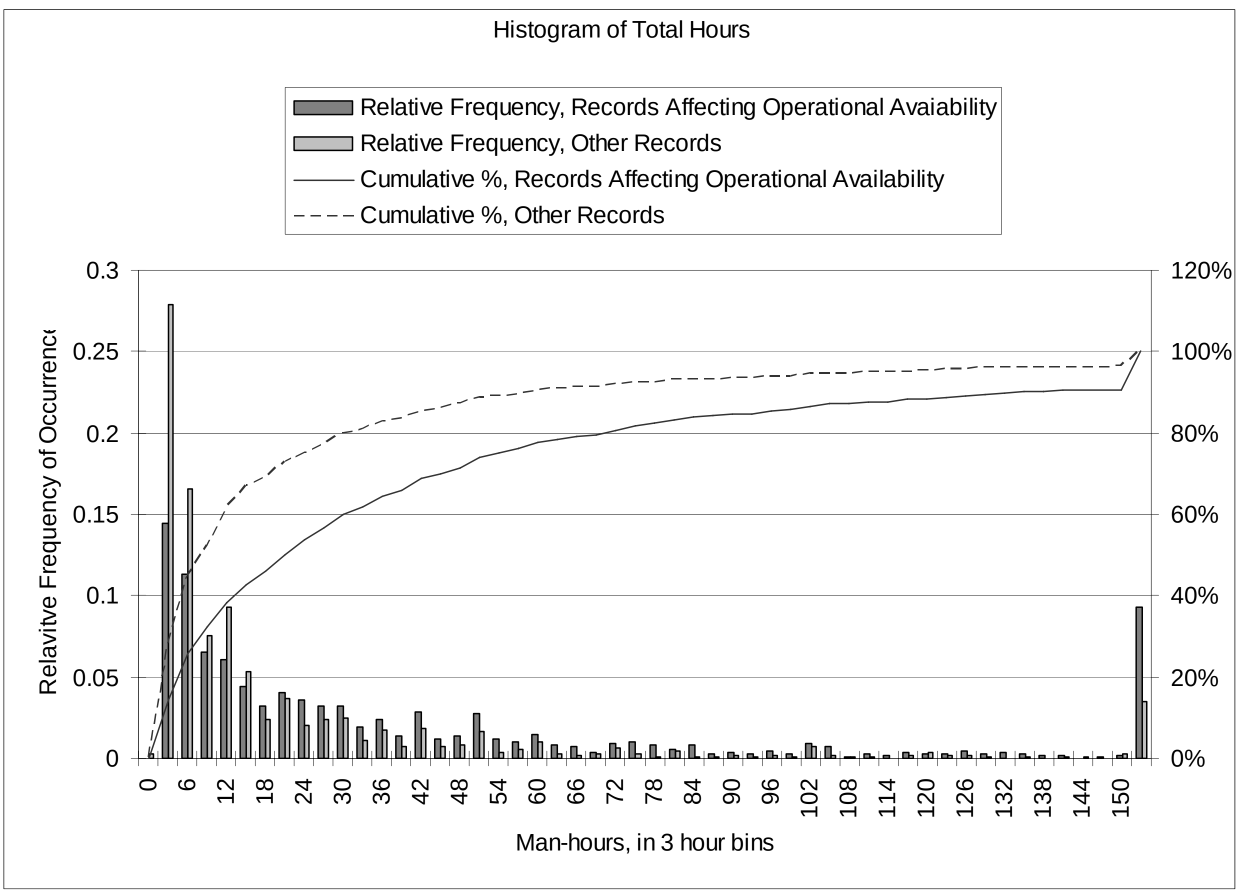
4.2 Total Hours

The difference in hours expended, as shown in [Table 6] and [Figure 2] below, makes intuitive sense. Maintenance actions reconciling debilitating degradation naturally require greater effort than others.

Table 6: Comparison of Total Hours

Total Hours	Average	70 percent at or below	90 percent at or below
All Records	43 hours	25 hours	80 hours
Records Affecting A_O	72 hours	46 hours	134 hours
Records Not Affecting A_O	31 hours	20 hours	60 hours

Figure 2: Histogram of Total Hours



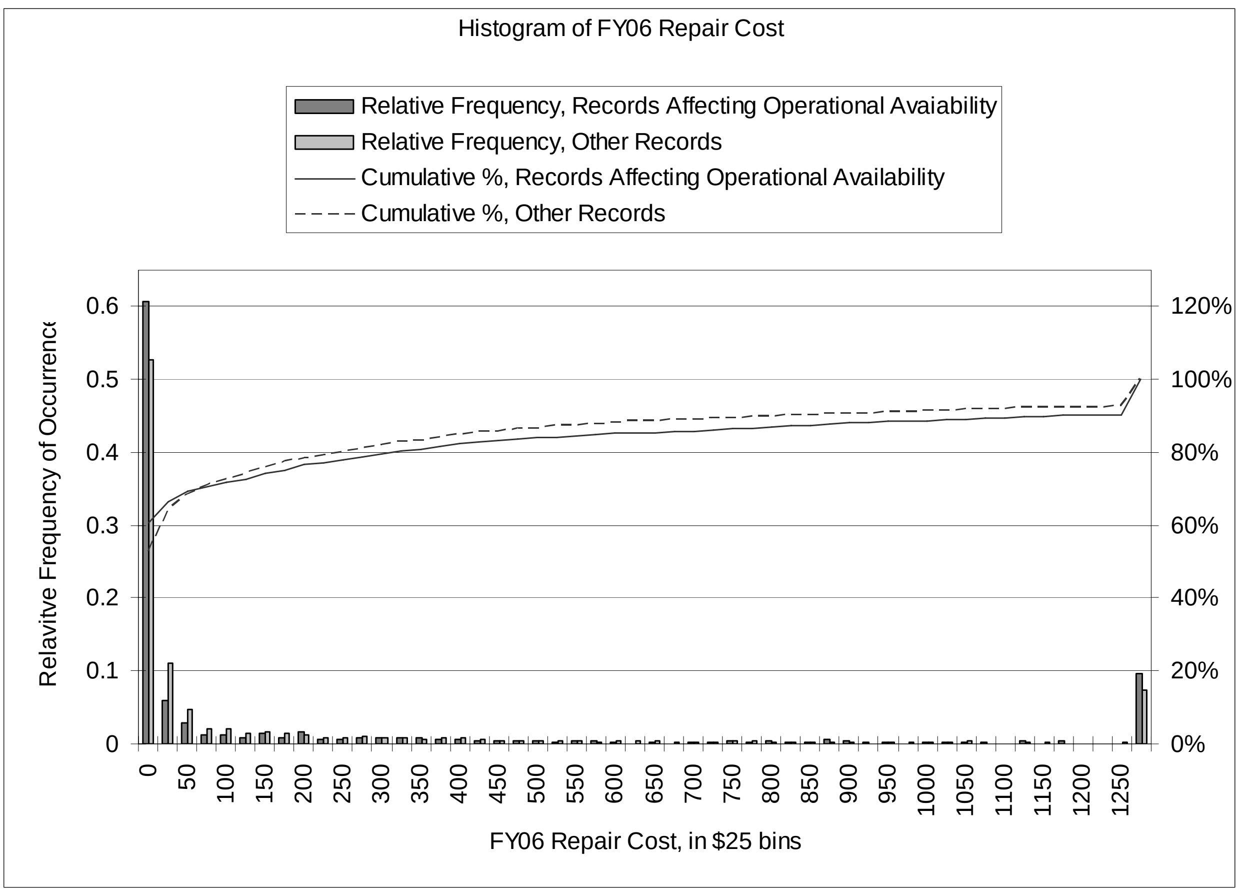
4.3 FY06 Repair Cost

Most repairs require relatively few, inexpensive parts, as shown in [Table 7] and [Figure 3] below. This is true regardless of the effect on operational availability. Those actions affecting A_O have a slight tendency to require more expensive parts.

Table 7: Comparison of FY06 Repair Cost

FY06 Repair Cost	Average	70 percent at or below	90 percent at or below
All Records	$654	$63	$900
Records Affecting A_O	$1042	$60	$1162
Records Not Affecting A_O	$502	$64	$802

Figure 3: Histogram of FY06 Repair Cost



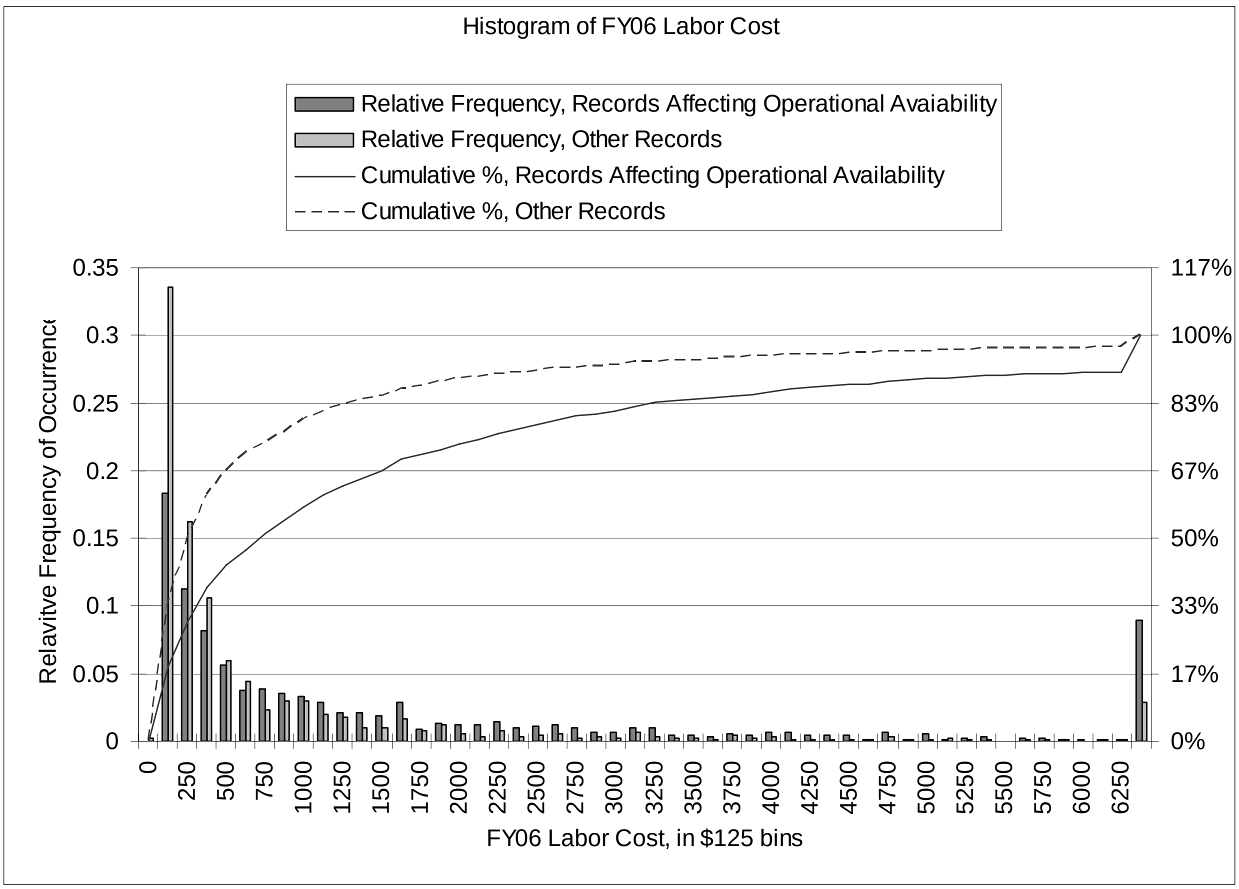
4.4 FY06 Labor Cost

Although average Labor Hours for A_O actions vs. non-A_O actions ratio at 2.3:1, the average FY06 Labor Cost compares at 2.7:1, as shown in [Table 8] and [Figure 4] below.

Table 8: Comparison of FY06 Labor Cost

FY06 Labor Cost	Average	70 percent at or below	90 percent at or below
All Records	$1597	$873	$3117
Records Affecting A_O	$2924	$1683	$5299
Records Not Affecting A_O	$1075	$624	$2182

Figure 4: Histogram of FY06 Labor Cost



Why is the labor cost ratio disproportionately higher than the labor hours ratio? The A_O actions require more expensive labor (IMA) to complete, as shown in [Table 9] below. The hourly labor rate is simply the FY06 Labor Cost divided by the Labor Hours.

Table 9: Comparison of Hourly Labor Rate

Hourly Labor Rate	Average	70 percent at or below	90 percent at or below
All Records	$33.86	$31.17	$45.02
Records Affecting A_O	$35.78	$31.17	$53.21
Records Not Affecting A_O	$33.10	$31.17	$31.44

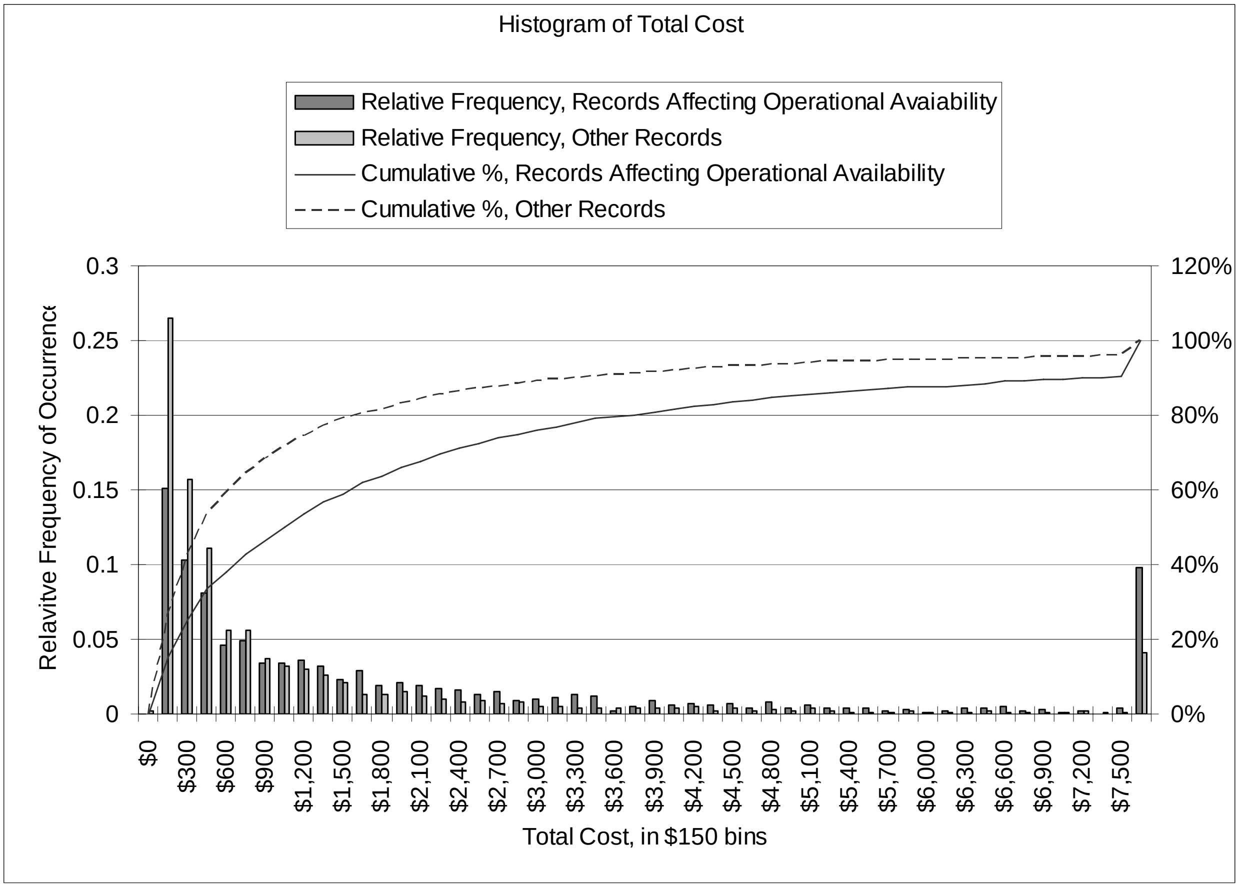
4.5 FY06 Total Cost

Not surprisingly, average FY06 Total Cost for A_O actions exceeds those for other maintenance actions, as shown in [Table 10] and [Figure 5] below.

Table 10: Comparison of FY06 Total Cost

FY06 Total Cost	Average	70 percent at or below	90 percent at or below
All Records	$2251	$1278	$4392
Records Affecting A_O	$3966	$2331	$7449
Records Not Affecting A_O	$1577	$967	$3274

Figure 5: Histogram of FY06 Total Cost



4.6 Availability

The records affecting operational availability were further analyzed to measure diesel engine availability as defined in Chapter 3. The availability figures varied greatly among hulls, as shown in [Table 11] below. Additional availability information can be found in Appendix A.

Table 11: Availability Measures by Hull Number

Measure	Average	Individual Worst	Individual Best
Mean Time Between Failures	205 days	SSN 723 5 days[1]	SSN 692 711 days
Mean Time To Repair	87 days	SSN 697 203 days	SSN 716 21 days[2]
Availability	0.623	SSN 723 0.071	SSN 773 0.963

Notes:

1. Several hulls had a negative mean time between failures (SSNs 699, 700, 702, 708, 709, 714, 725, 755, 764, 765, and 772), meaning that on average, a second maintenance action would begin prior to completing the first one. These data for these hulls are not included in this table.
2. SSN 689 had only one maintenance action affecting operational availability, lasting 10 days. The datum for this hull is not included in this table.

Chapter 5 Conclusion

5.1 Findings

1. Diesel engine maintenance actions adversely affecting operational availability, on average:
   - Require more labor hours
   - Utilize more expensive repair parts
   - Require more expensive labor
   - Are not necessarily handled more expeditiously than other maintenance actions; on the contrary: they actually take slightly longer to reconcile.
2. Most diesel engine maintenance actions are inexpensive and require minimal effort.
3. Diesel engine availability is difficult to measure. What can be measured varies greatly from submarine to submarine.

5.2 Recommendations

1. Develop a means of reporting the relevance of the maintenance action to operation availability.
2. Improve the methods of data entry for this system. Analysis of the data was hindered by data entry errors. This improvement could be implemented through the Navy's diesel repair course.

5.3 Future Work

1. Analyze the outlying 10 percent of the maintenance actions for each of the key metrics to discover any trends.
2. Continue further analysis of other maintenance codes to identify issues (see Appendices B through G).
3. Utilize similar methodology to examine diesel generator maintenance records.
4. Utilize similar methodology to examine other pieces of equipment onboard nuclear submarines and other naval vessels.

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The author also wishes to thank his family for enduring the thesis process.

Above all, the author's desire is to glorify God through this endeavor.

"I know, O LORD, that a man's life is not his own;

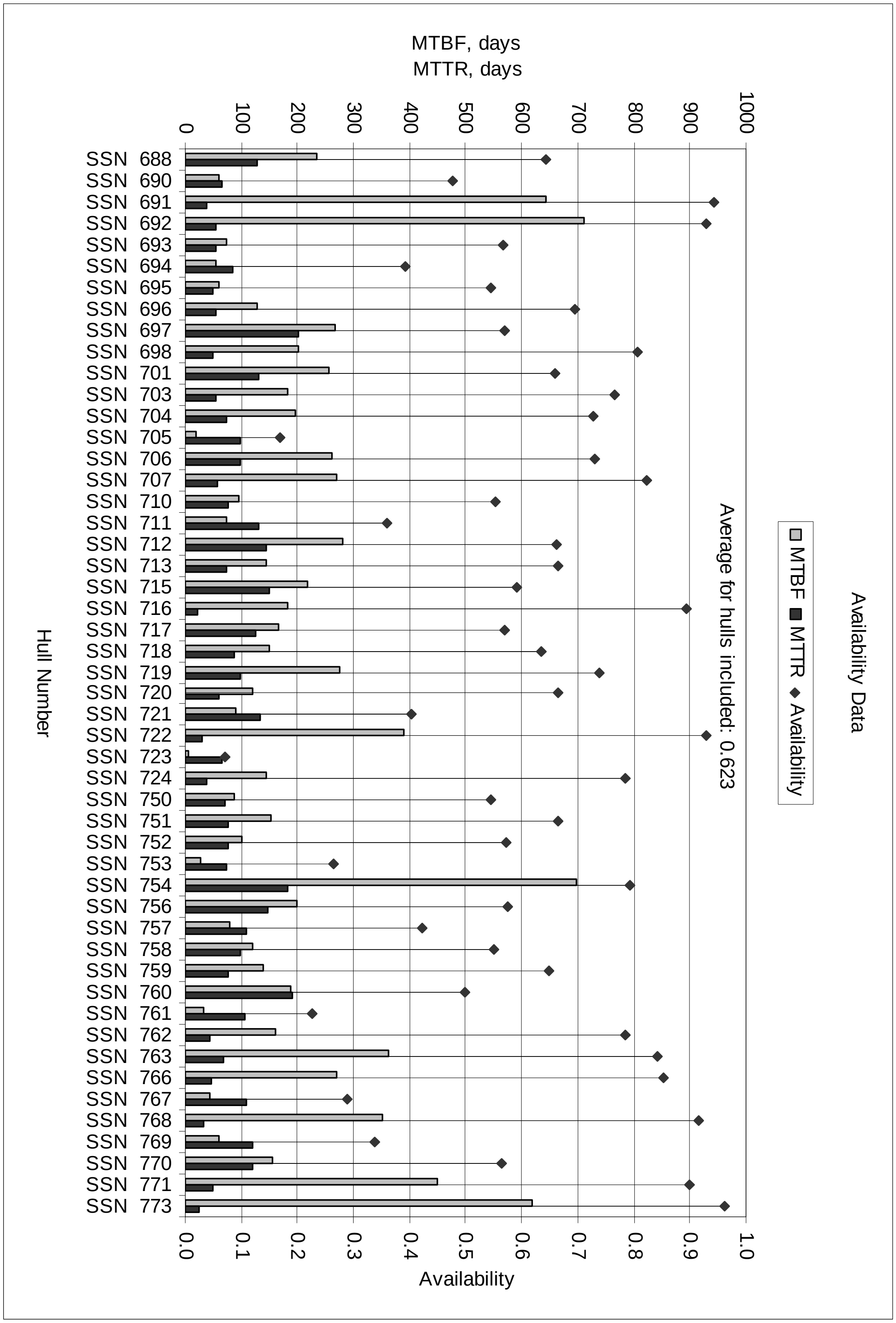
it is not for man to direct his steps."

Jeremiah 10:23

Appendices

Appendix A: Availability Data by Submarine Hull

Figure 6: Availability Data by Submarine Hull

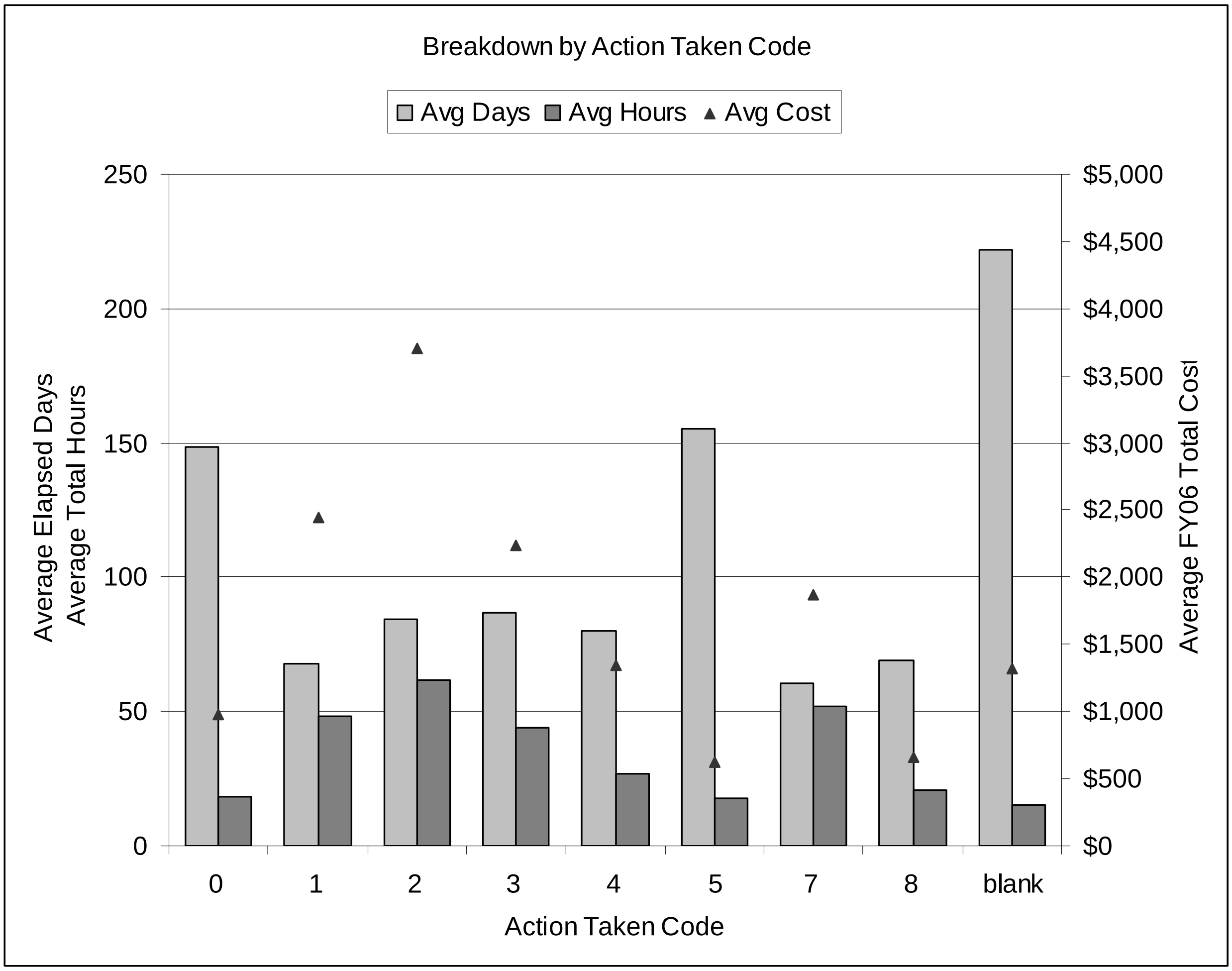


Appendix B: Action Taken Code

Table 12: Action Taken Code Frequency and Meaning

Code	# of Occurrences	Meaning
0	407	None of the Below
1	2344	Maintenance Action Completed; Parts Drawn from Supply
11	1	X this is supposed to be 1
1A	8	Maintenance Requirement Could Have Been Deferred
1B	44	Maintenance Requirement Was Necessary
2	406	Maintenance Action Completed Required Parts Not Drawn from Supply (local manufacture, pre-expended bins, etc.)
2A	2	Maintenance Requirement Could Have Been Deferred
2B	13	Maintenance Requirement Was Necessary
2T	2	The Equipment Being Reported Had a Time Meter
3	640	Maintenance Action Completed; No Parts Required
3A	2	Maintenance Requirement Could Have Been Deferred
3B	9	Maintenance Requirement Was Necessary
3T	1	The Equipment Being Reported Had a Time Meter
4	338	Canceled
5B	1	Fully Completed Alteration
7	5	Maintenance Action Completed; 2-M (Miniature/ Microminiature Electronic Modules) Capability Utilized.
74	1	X this is supposed to be 7e
7A	6	Parts Drawn from Supply Utilized
7B	4	Parts Not Drawn from Supply Utilized
7C	5	Automatic Test Equipment (ATE) Utilized
7D	33	ATE and Parts Drawn from Supply Utilized
7E	6	ATE and Parts Not Drawn from Supply Utilized
8	1	Periodic Time Meter/Cycle Counter reporting
blank	254	(Not allowed by the instruction)

Figure 7: Breakdown by Action Taken Code



Notes:

1. Action Taken Code 5 represents only one maintenance action.
2. Action Taken Code 7 represents the most effective use of manpower – it has the highest man-hours per Elapsed Days ratio.
3. The high cost of Action Taken Code 2 may be explained y the repair parts coming from outside the usual supply channels.
4. A blank Action Taken Code – not allowed by the instruction – seems to be an identifier of negligence. These maintenance actions took the least amount of man-hours but were the longest to resolve.

Appendix C: Cause Code

This is a code best describing the cause of the failure or malfunction when the need for maintenance was first discovered. When more than one cause contributed to the failure or malfunction, the primary or overriding one is selected.

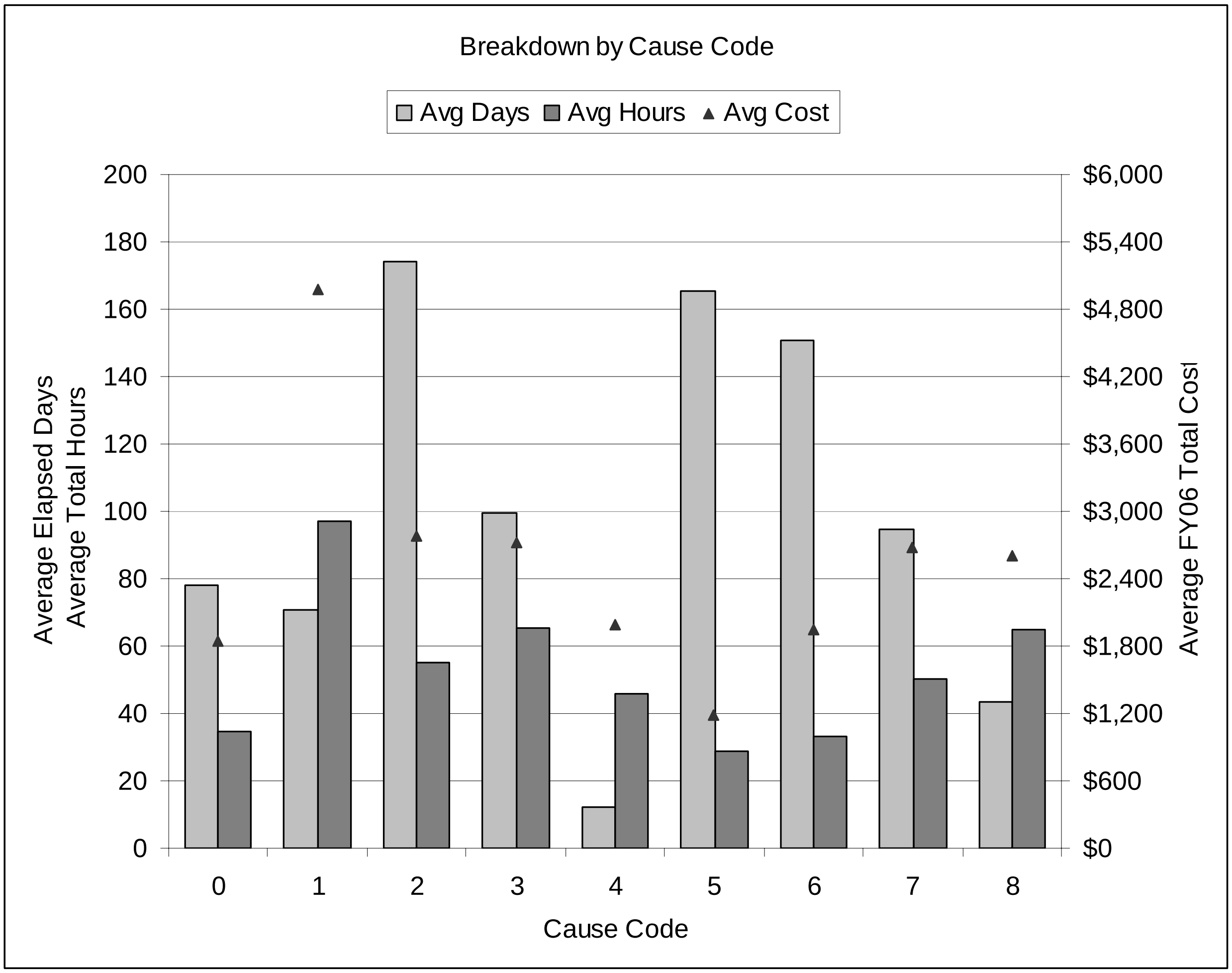
Table 13: Cause Code Frequency and Meaning

Code	# of Occurrences	Meaning
0	2478	OTHER OR NO MALFUNCTION. Needs to be explained in the Remarks field. Examples: 1) Fatigue or physical stress brought on by prolonged work periods or excessive heat, humidity, or noise. 2) Desire to save time and effort by taking shortcut and jury-rigging equipment. 3) Malfunction occurred when installing a field change to improve equipment effectiveness, or when the cause resulted from a personnel oriented deficiency affecting safety due to fatigue, etc.
1	93	ABNORMAL ENVIRONMENT. Exposure to conditions more extreme than those reasonably expected in the normal shipboard environment (e.g., electrical equipment sprayed by salt water, or compartment flooded).
2	149	MANUFACTURER/INSTALLATION DEFECTS. Material not assembled or manufactured per specifications, or installed improperly by IMA or Depot (e.g., motor with open circuit armature).
3	57	LACK OF KNOWLEDGE OR SKILL. Failure or malfunction of the equipment due to insufficient training, experience, or physical coordination of the operator, maintainer, or other personnel (e.g., not knowing equipment limitations such as the danger of a low speed wheel on a high speed grinder).

Table 13: Cause Code Frequency and Meaning (continued)

Code	# of Occurrences	Meaning
4	3	COMMUNICATIONS PROBLEM. A breakdown in the passing, receiving, or understanding of information (e.g., failure to hear or receive a complete message due to noise or mechanical or electrical interference).
5	26	INADEQUATE INSTRUCTION/PROCEDURE. The instruction or procedures guide has omissions, errors, ambiguities, or other deficiencies (e.g., technical manual omits lubricant type).
6	62	INADEQUATE DESIGN. Material manufactured and installed per specifications failed prematurely during normal usage under normal environmental conditions (e.g., steam piping orientation precludes adequate draining during warm-up).
7	1658	NORMAL WEAR AND TEAR. Material requires replacement after long service and/or as a result of PMS (e.g., pump wear rings replaced during PMS).
8	7	CORROSION CONDITION.

Figure 8: Breakdown by Cause Code



Notes:

1. The apparently most effective codes, Cause Code 4 and 8, represent only three and seven maintenance actions, respectively.
2. Cause Code 1, with 93 maintenance actions, represents a relatively effective man-hours per Elapsed Day ratio.
3. Cause Code 1 would include maintenance actions resulting from a flooded diesel, which may explain its higher average costs.

Appendix D: Priority Code

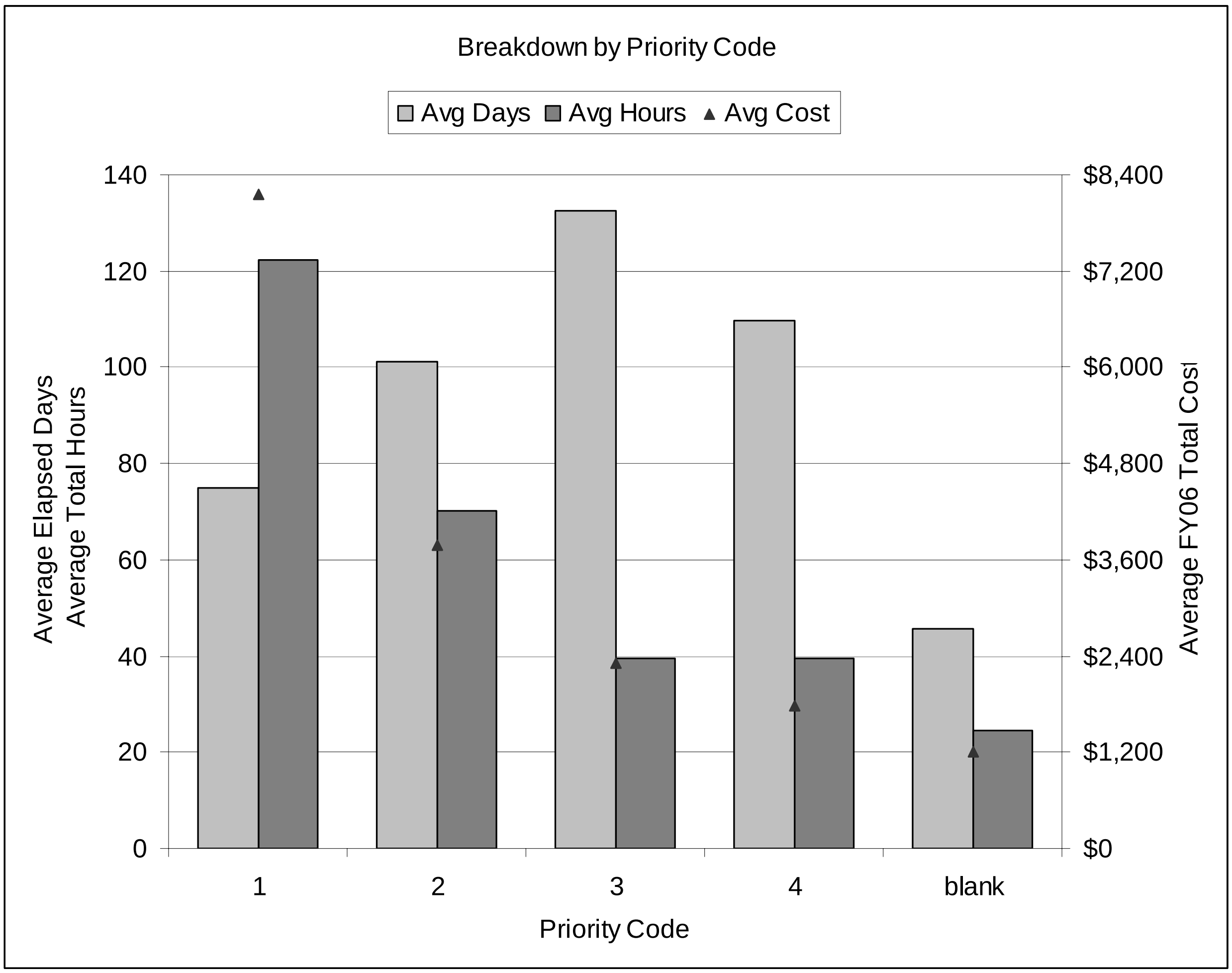
Table 14: Priority Code Frequency and Meaning

Code	# of Occurrences	Meaning
1	104	MANDATORY. Critical safety or damage control item. Required for performance of ship's mission. Required to sustain bare minimum acceptable level of human needs and sanitation. C-4 CASREP (Casualty Report) on equipment.
2	969	ESSENTIAL. Extremely important safety or damage control item. Required for sustained performance of ship's mission. Required to sustain normal level of basic human needs and sanitation. Required to maintain overall integrity of ship or a system essential to ship's mission. Will contribute so markedly to efficient and economical operation and maintenance of a vital ship system that the pay-off in the next year will overshadow the cost to accomplish. Required for minimum acceptable level of preservation and protection. C-3 CASREP on equipment.
3	858	HIGHLY DESIRABLE. Important safety or damage control item. Required for efficient performance of ship's mission. Required for normal level of human comfort. Required for overall integrity of equipment or systems that are not essential, but are required as backups in case of primary system failure. Will contribute so markedly to efficient and economical operation and/or maintenance of a vital ship system that the payoff in the next year will at least equal the cost to accomplish. Will effect major reduction in future ship maintenance in an area or system that presently cannot be maintained close to acceptable standards. Required to achieve minimum acceptable level of appearance. C-2 CASREP on equipment.

Table 14: Priority Code Frequency and Meaning (continued)

4	1005	DESIRABLE. Some contribution to efficient performance. Some contribution of normal level of human comfort and welfare. Required for overall integrity of other than an essential system or its backup system. Will contribute to appearance in an important area. Will significantly reduce future maintenance.
Blank	1597	

Figure 9: Breakdown by Priority Code



Notes:

1. The decreasing costs and decreasing efficiency for decreasing Priority Code makes sense.

Appendix E: Safety Code

This code is used if the maintenance action describes a problem or condition which has caused, or has the potential to cause serious injury to personnel or material.

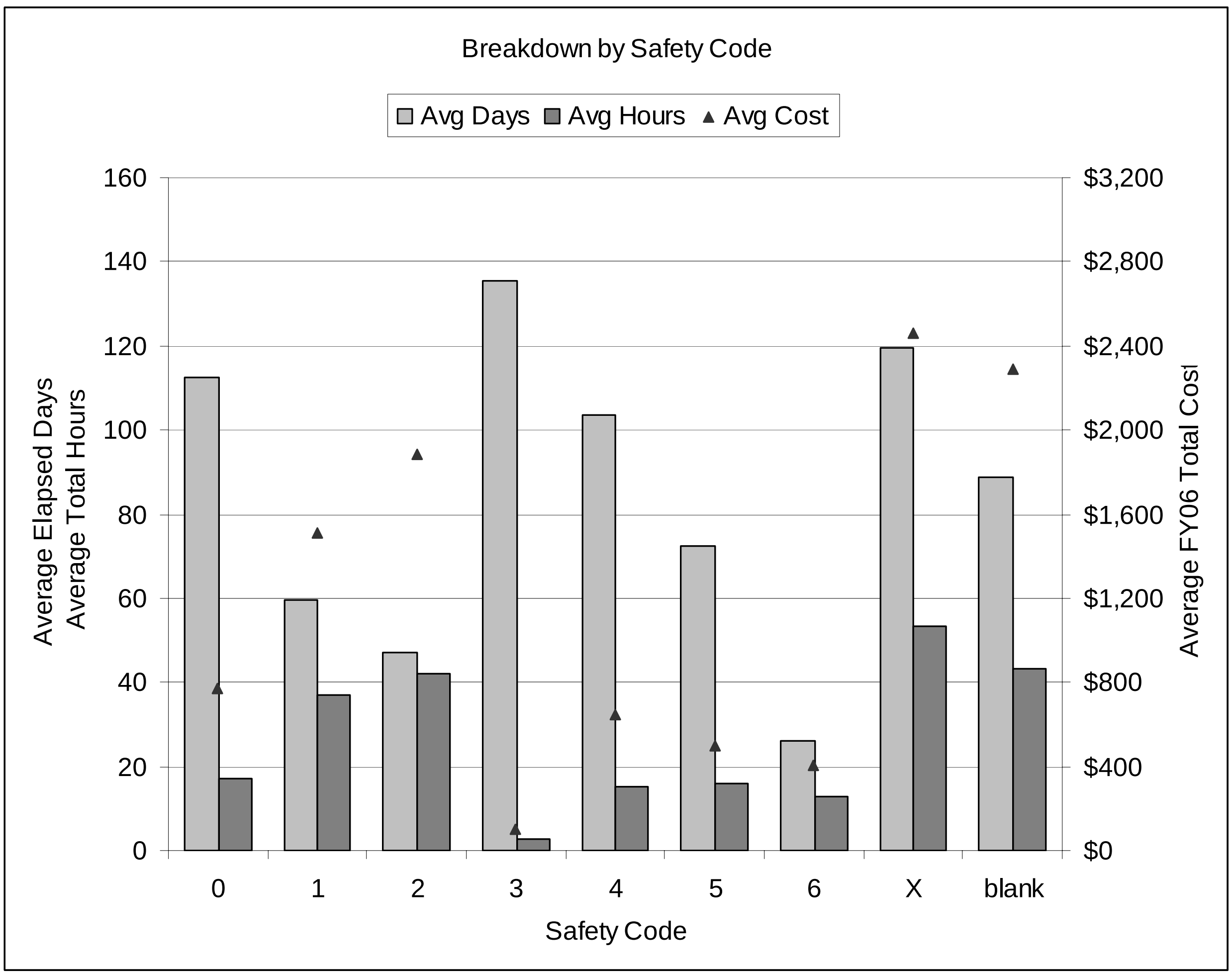
Table 15: Safety Code Frequency and Meaning

Code	# of Occurrences	Meaning
1	13	CRITICAL SAFETY OR HEALTH DEFICIENCY-CORRECT IMMEDIATELY. This category identifies deficiencies which present a critical safety hazard to personnel or machinery, or a health hazard to personnel, and which must be corrected immediately. This code is used for items such as electric shock hazards, inoperative interlocks or safety devices, missing or damaged lifelines, inoperable escape scuttles, refrigerants (air conditioning or refrigeration) leaking into confined spaces, leaking components containing PCBs, and the like. All efforts must be exerted to correct these items prior to any other maintenance deficiencies. Suspension of use of the equipment/system/space is mandatory.
2	5	SERIOUS SAFETY OR HEALTH DEFICIENCY-SUSPENSION OF EQUIPMENT/SYSTEM/SPACE USE IS REQUIRED. This category deals with serious safety hazards to personnel or machinery, or health hazards which must be corrected prior to resuming use of the equipment/system/space.
3	10	MODERATE SAFETY OR HEALTH DEFICIENCY-WAIVER OF EQUIPMENT/SYSTEM/SPACE USE IS GRANTED PENDING CORRECTION OF THE ITEM. This category is used in cases where the equipment/system/space can be operated or utilized in a satisfactory manner without greatly risking physical injury, serious damage to the equipment/system/space, or greatly risking the health of personnel.

Table 15: Safety Code Frequency and Meaning (continued)

4	6	MINOR SAFETY OR HEALTH DEFICIENCY. This is a category of safety or health deficiencies which must be corrected when resources become available.
5	31	NEGLIGIBLE SAFETY OR HEALTH DEFICIENCY. This category identifies deficiencies which are noted for record purposes and may be corrected when other work is accomplished on the equipment/system/space.
6	1	Varies – local use
X	15	SAFETY RELATED INDICATOR
0	57	MAINTENANCE ACTION IS NOT SAFETY RELATED.
blank	4395	

Figure 10: Breakdown by Safety Code



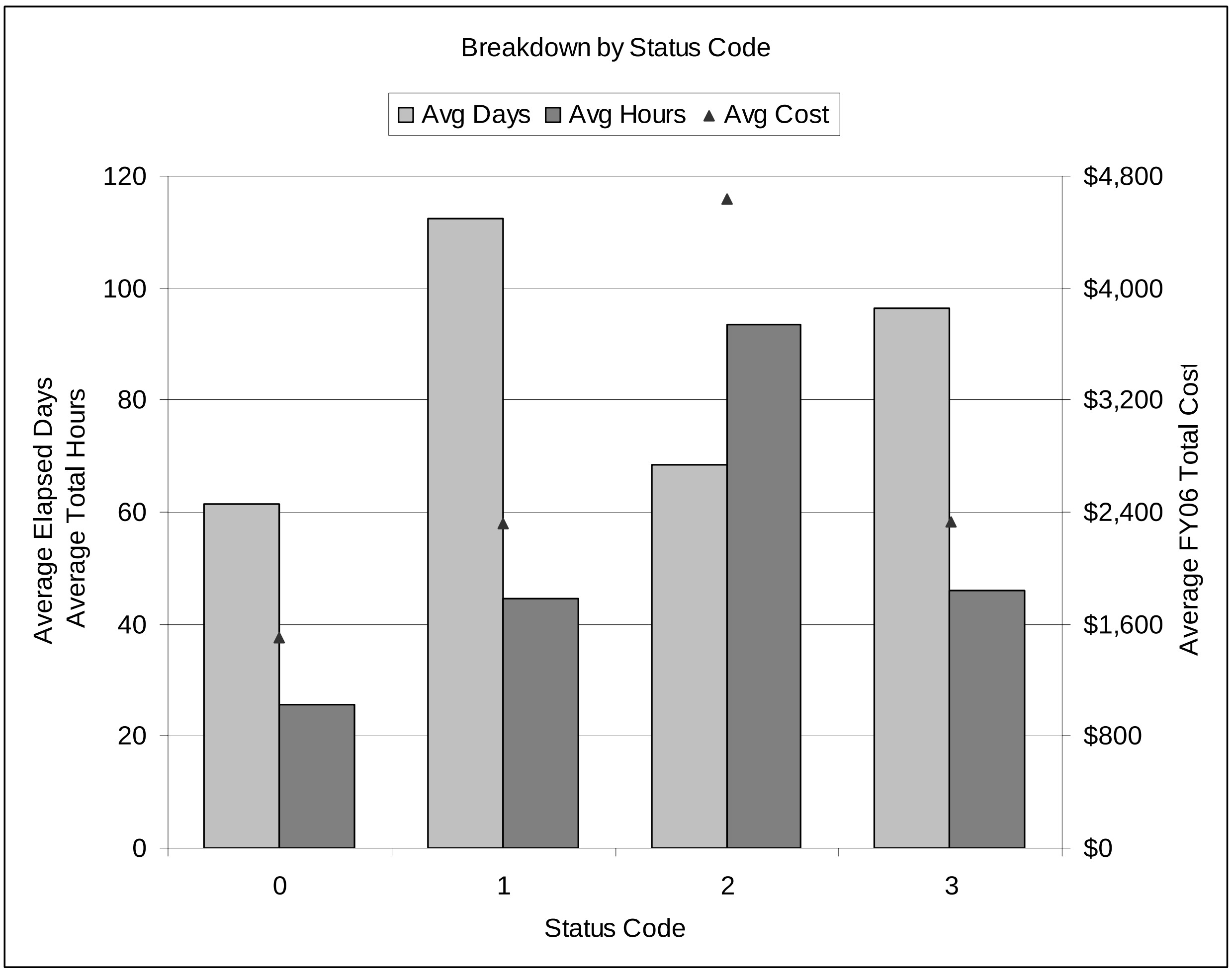
Appendix F: Status Code

This code most accurately describes the effect of the failure or malfunction on the operational performance capability of the equipment when the need for maintenance was first discovered.

Table 16: Status Code Frequency and Meaning

Code	# of Occurrences	Meaning
0	1581	Not Applicable (use if reporting printing services, etc.)
1	2057	Operational
2	423	Non-Operational
3	472	Reduced Capability

Figure 11: Breakdown by Status Code



Status Code 2 (non-operational) is both the most effective and most expensive, which makes sense.

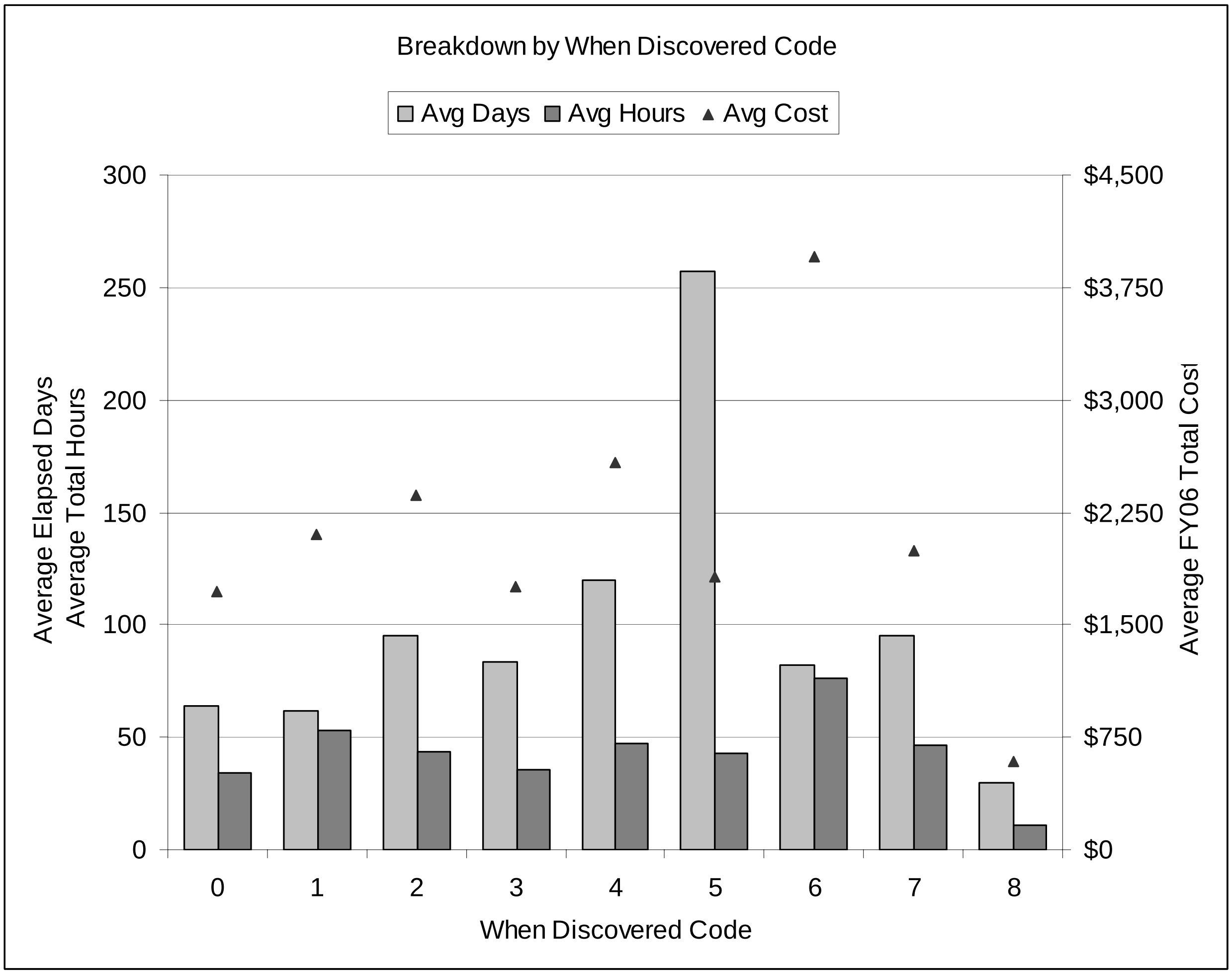
Appendix G: When Discovered Code

This code identifies when the need for maintenance was discovered.

Table 17: When Discovered Code Frequency and Meaning

Code	# of Occurrences	Meaning
0	1721	Not Applicable (use when reporting printing services, etc.)
1	91	Lighting Off or Starting
2	949	Normal Operation
3	82	During Operability Tests
4	1372	During Inspection
5	8	Shifting Operational Modes
6	271	During PMS
7	8	Securing
8	31	During AEC (Assessment of Equipment) Program

Figure 12: Breakdown by When Discovered Code



When Discovered Code 6 represents both the most effective and the most expensive maintenance actions. This makes sense if the PMS uncovers an underlying problem not apparent during operation.

Bibliography

1. http://www.navy.mil/navydata/cno/n87/themes/costeff.html
2. http://www.nucleartourist.com/areas/diesel.htm
3. ADM K. H. Donald, Director, Naval Nuclear Propulsion, remarks at the Naval Submarine League Corporate Benefactors' Recognition Days, February 15, 2005, as printed in The Submarine Review, Naval Submarine League, April 2005, p. 20.
4. RADM Joseph Walsh, Director, Submarine Warfare Division, remarks at the Naval Submarine League Corporate Benefactors' Day, February 1, 2006, as printed in The Submarine Review, Naval Submarine League, April 2006, p. 33.
5. Angus Hendrick, NAVSEA 08 (Naval Reactors) engineer, telephone conversation conducted July 26, 2005.
6. OPNAV Instruction 9220.3 dated December 19, 2003 titled Propulsion and Auxiliary Plant Inspection and Inspector Certification Program.
7. NAVSEA Instruction 4790.8B dated November 13, 2003 titled Ships' Maintenance and Material Management (3-M) Manual.
8. Polmar, Norman. The Naval institute Guide to the Ships and Aircraft of the U.S. Fleet, 15th edition. US Naval Institute, Annapolis, MD, 1993.
9. http://www.hazegrey.org/
    a. shipbuiliding/eb.htm
    b. shipbuilding/nnsb2.htm
    c. worldnav/usa/decom.htm